

TARGET CHARACTERIZATION AND FOLLOW-UP  
OBSERVATIONS IN SUPPORT OF THE KEPLER MISSION

NCC2-1390

Annual Report

No. 2

01 December 2003 to 30 November 2004

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December 2004

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<p>The Smithsonian Astrophysical Observatory is a member of the Harvard-Smithsonian Center for Astrophysics</p>
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## TARGET CHARACTERIZATION AND FOLLOW-UP OBSERVATIONS IN SUPPORT OF THE KEPLER MISSION

This report covers work carried out at the Smithsonian Astrophysical Observatory during the period 1 December 2003 to 30 November 2004

SAO is leading the effort to prepare the Kepler Input Catalog, which will be used to select the targets actually observed for planetary transits by Kepler. In March 2004 a team led by SAO was selected to carry out a ground-based multi-band photometric survey of the Kepler target region and to use the new photometry along with other available information to estimate the astrophysical characteristics of candidate target stars for inclusion in the Kepler Input Catalog, which is scheduled for delivery in December 2006.

SAO is also active in making follow-up observations of transiting planet candidates identified by several ground-based photometric surveys. The goal is to learn how to identify stellar systems that mimic transiting planets, since this will be a major challenge for the interpretation of candidates identified by Kepler.

### Ground-Based Photometric Survey

Production observing for the ground-based multi-band photometric survey began in May 2004, using the 4Shooter CCD camera on the 48-inch telescope at SAO's Whipple Observatory atop Mount Hopkins, Arizona. During the summer shutdown in August 2004 the MiniCam CCD camera, on loan from the MMT, was brought into operation on the 48-inch telescope as an interim replacement for the venerable 4Shooter. It was used for production observing during the fall 2004 season.

Observations were made with the SDSS g, r, i, and z filters, supplemented by our custom D51 filter centered on the Mg b features, which are luminosity sensitive. Based on our initial experience with the SDSS u filter in the fall of 2003, we decided to postpone observations with that filter.

Two observers, Carl Hegenrother and Gil Esquerdo, were hired and trained to make the photometric observations. Detailed observing plans and schedules for each night were prepared by Dave Latham, who maintained a database of the target regions that had been successfully observed. Altogether observations were obtained on 53 nights during the reporting period.

The preparation of the Kepler Input Catalog proceeds as follows. The CCD images are processed by Mark Everett at the Planetary Sciences Institute in Tucson using a pipeline that he developed specifically for this purpose. David Monet at the United

States Naval Observatory in Flagstaff, Arizona, made important contributions to the astrometric section of the pipeline.

The reduced data, in the form of instrumental magnitudes and positions, are shipped to Tim Brown in Boulder, Colorado, where the data are ingested into an archival database developed specifically for this purpose. Tim also developed codes for deriving nightly extinction coefficients from the observations of standard regions, and codes for removing the effects of atmospheric extinction.

After the instrumental magnitudes have been transformed onto the standard SDSS magnitude system, they are then used to estimate the Kepler magnitude, effective temperature, reddening, extinction, surface gravity, metallicity, and stellar radius using codes under development by Tim.

The photometric results and astrophysical parameters are next shipped to David Monet in Flagstaff, where they are merged with existing information, such as the infrared photometry from the 2MASS Catalog and astrometry from the UCAC and USNO-B Catalogs, to form the Kepler Input catalog. The addition of the astrometric information, especially proper motions, then provides the opportunity for some fine tuning of the estimates of the stellar characteristics.

### KeplerCam

SAO also undertook a project to build KeplerCam, a new state-of-the-art CCD camera, scheduled to be available for production observing on the 48-inch telescope starting in April 2005. One of the advantages of KeplerCam is that it utilizes a single monolithic chip with four amplifiers, so there are no gaps in the images. This camera is being built in John Geary's laboratory at SAO, with Andy Szentgyorgyi as the Project Scientist, and with the participation of Steve Amato, Kevin Bennett, and Brian McLeod. The operating software for both MiniCam and KeplerCam are the responsibility of Ted Groner at the Whipple Observatory.

The observing with the 48-inch has been supported enthusiastically by the staff of the Whipple Observatory, especially by Emilio Falco, Ted Groner, Wayne Peters, and Bob Hutchins, at no cost to the project. The time on the 48-inch telescope is under control of the CfA Time Allocation Committee, and has been provided at no cost to the project.

### Follow-Up Observations

SAO first began making spectroscopic follow-up observations of transiting planet candidates identified by ground-based photometric surveys in 1999. It soon became clear that the vast majority of the candidates were actually stellar systems masquerading as transiting planets. A common false positive is an F star primary eclipsed by an M dwarf

companion. Triple systems that include an eclipsing binary diluted by the light of a brighter third star are also common, usually hierarchical triples, but also chance alignments. Although triple systems that include eclipsing binaries may be intrinsically rare, the photometric surveys are very efficient at finding them. Physical triples can be difficult to confirm, because the angular separations between the components are small, and the lines in the spectra of the eclipsing stars tend to be faint and broadened by rotation due to tidal synchronization.

During the reporting period members of the SAO team were authors on eleven papers reporting the results of follow-up observations of transiting planet candidates. Several of these reported the confirmation of transiting planets, both from the Ogle survey (Ogle 113 and 56) and the TrES consortium (TrES-1). Other papers reported transit candidates that proved to be stellar systems. Particularly significant for the identification of false positives are the sophisticated tools developed by Willie Torres for the analysis of blended triples. These papers are listed in the attached bibliography. Seven actually appeared in print during the reporting period, while the other seven were prepared and/or submitted during the reporting period. Seven are in the *Astrophysical Journal*, while the other seven were presented at conferences and meetings.

### Spectroscopic Stellar Classification

SAO is responsible for high-resolution spectroscopic classification of many of the target candidates in the Kepler Input Catalog. Towards this end a large effort was invested in bringing the Hectochelle multi-fiber CCD spectrograph into operation on the MMT at SAO's Whipple Observatory atop Mount Hopkins. Engineering runs in November 2003 and March 2004 were successful in obtaining stellar spectra, but unfortunately not with the radial-velocity order that we use for stellar classification and velocity work. The problem was that the special multi-layer coatings on the collimator and camera mirrors developed a green coating that absorbed more than 80% of the light in a band centered on the wavelength region in the green that we use.

The two large Hectochelle mirrors were removed and sent out for recoating during the summer of 2004. They were successfully remounted, installed in the spectrograph, and aligned in September and October 2004, in time for a successful engineering run in November 2004. The first production observing for Kepler is scheduled over four nights in March 2005.

In the meantime the work to produce a new library of synthetic spectra for the analysis of Hectochelle observations is proceeding. The fine tuning of the line list for the Hectochelle radial-velocity order is being carried out by Jon Morse at Arizona State and is now nearly complete. Bruce Carney at the University of North Carolina and John Laird at Bowling Green State University are tooling up to produce a homogeneous grid of new stellar models. The actual calculation of the spectra will be done on computers at SAO.

An NSF proposal was submitted requesting funds for implementing the cross-dispersed mode of Hectochelle, which would have made the instrument a few times more effective for very precise radial-velocity observations in fields with only a couple dozen targets. This mode would have been useful for follow-up observations of Kepler candidates. This proposal was not funded.

A more detailed analysis of the initial follow-up observations needed to sort out false positives led to the conclusion that lots of telescope time would be needed for radial velocity observations with moderate precision, typically in the range 300 to 1500 m/s. This same conclusion was reached independently by Nick Gautier. The venerable CfA Digital Speedometers, which have been in operation since the late 1970s, provide this level of performance, but are limited to stars brighter than about 13<sup>th</sup> magnitude because of the limited sensitivity of the photocathodes used in the detectors.

Anticipating the need of a new state-of-the-art CCD spectrograph for follow-up of large numbers of candidates identified by Kepler, we submitted an internal proposal for SAO funds to build the Tillinghast Reflector Echelle Spectrograph (TRES). This proposal was funded (almost 900K), and the instrument is now being built with Andy Szentgyorgyi as Project Scientist. It is scheduled to come into operation by the time Kepler launches. We expect that it will be a workhorse for follow-up spectroscopy of transiting planet candidates.

We are convinced that TRES will be much more important to the success of the Kepler mission than the cross-dispersed mode of Hectochelle would have been. Thus we are already redirecting some of our Kepler resources into the TRES development.

#### Programmatics

Latham attended the Systems Requirements Review in Boulder in October 2003, and a Stellar Classification Program team meeting in Tucson in November 2003. He hosted a Science Team meeting in Cambridge in June 2004. He participated in an incremental Preliminary Design Review at Ames in September 2004, a Science Team meeting in Boulder in October 2004, and the Preliminary Design Review in Boulder in October 2004. Latham also participated in the Ground Segment Monthly Management Reviews via telephone, providing review charts of the progress with the Stellar Classification Program in advance for presentation at all of these meetings. Latham's Kepler funds were used to support travel by John Geary and John Chappel so that they could participate in various review meetings for the project.

#### Education and Public Outreach

Latham presented a seminar at the CfA on the Kepler mission in January 2004. He made a presentation on Kepler to key congressional staffers in June 2004. He highlighted the role of Kepler in his presentation to Bioastronomy 2004: The Search for

Habitable Planets in Iceland in July 2004. He lectured on Kepler and the Search for Habitable Planets at the CfA Monthly Observatory Night, kicking off the fall season in September 2004 to an overflow audience.

Publications that appeared in print during the reporting period

Charbonneau, D., Brown, T. M., Dunham, E. W., Latham, D. W., Looper, D. L., & Mandushev, G., 2004. Astrophysical False Positives Encountered in Wide-Field Transit Searches, in THE SEARCH FOR OTHER WORLDS: Fourteenth Astrophysics Conference, AIP Conference Proceedings, Volume 713, p. 151

Konacki, M., Sasselov, D. D., Torres, G., Jha, S., & Kulkarni, S. R., 2003. High-quality Light Curve of the OGLE-TR-56b Planetary Transit American Astronomical Society Meeting 203

Konacki, M., Torres, G., Sasselov, D. D., & Jha, S., 2003. High-Resolution Spectroscopic Follow-up of OGLE Planetary Transit Candidates in the Galactic Bulge: Two Possible Jupiter-Mass Planets and Two Blends, *Astrophysical Journal*, 597, 1076

Konacki, M., Torres, G., Sasselov, D. D., Pietrzynski, G., Udalski, A., Jha, S., Ruiz, M. T., Gieren, W., & Minniti, D., 2004. The Transiting Extrasolar Giant Planet around the Star OGLE-TR-113, *Astrophysical Journal*, 609L, 37

Torres, G., Konacki, M., Sasselov, D. D., & Jha, S., 2004. New Data and Improved Parameters for the Extrasolar Transiting Planet OGLE-TR-56b, *Astrophysical Journal*, 609, 1071

Torres, G., Konacki, M., Sasselov, D. D., Jha, S., 2004. OGLE-TR-56, in THE SEARCH FOR OTHER WORLDS: Fourteenth Astrophysics Conference, AIP Conference Proceedings, Volume 713, p. 165

Torres, G., Konacki, M., Sasselov, D. D., & Jha, S., 2003. The transiting planet OGLE-TR-56b, American Astronomical Society Meeting 203

Papers that were prepared and/or submitted during the reporting period:

Alonso, R., Brown, T. M., Torres, G., Latham, D. W., Sozzetti, A., Mandushev, G., Belmonte, J. A., Charbonneau, D., Deeg, H. J., Dunham, E. W., et al., 2004. TrES-1: The Transiting Planet of a Bright K0 V Star, *Astrophysical Journal*, 613L, 153

Sozzetti, A., Yong, D., Torres, G., Charbonneau, D., Latham, D. W., Allende Prieto, C., Brown, T. M., Carney, B. W., & Laird, J. B., 2004. High-Resolution Spectroscopy of the Transiting Planet Host Star TrES-1, *Astrophysical Journal*, 616L, 167

Sozzetti, A., Latham, D. W., Torres, G., Stefanik, R. P., Boss, A. P., Carney, B. W., Laird, J. B., 2004. A Keck/HIRES Doppler Search for Planets Orbiting Metal-Poor Dwarfs, Proceedings of the Symposium "The Three-dimensional Universe with Gaia", 4-7 October 2004, Observatoire de Paris-Meudon, France (ESA SP-576)

Sozzetti, A., Latham, D. W., Torres, G., Stefanik, R. P., Boss, A. P., Carney, B. W., Laird, J. B., 2004. A Keck/HIRES Doppler Search for Planets Orbiting Metal-Poor Dwarfs, American Astronomical Society Meeting 204

Sozzetti, A., Latham, D. W., Torres, G., Stefanik, R. P., Boss, A. P., Carney, B. W., & Laird, J. B., 2003. When Do Planets Form? A Search for Extra-solar Planets Around Metal-Poor Stars, in the Proceedings of the XIXth IAP Symposium - Extrasolar Planets: Today and Tomorrow, ASP Conference Series

Torres, G., Konacki, M., Sasselov, D. D., & Jha, S., 2004. Testing Blend Scenarios for Extrasolar Transiting Planet Candidates. I. OGLE-TR-33: A False Positive, Astrophysical Journal, 614, 979

Torres, G., Konacki, M., Sasselov, D. D., & Jha, Saurabh, 2005. Testing Blend Scenarios for Extrasolar Transiting Planet Candidates. II. -- OGLE-TR-56, Astrophysical Journal Submitted.